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Stratigraphy of the Lefroy and Cowan palaeodrainages, Western Australia

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Abstract

This paper revises the stratigraphy of the Lefroy and Cowan palaeodrainages, and compares it with that of the Eucla and Bremer Basins. The definition of the Eundynie Group is modified, and the terms Redmine Group, Revenge Formation, Gamma Island Formation, Polar Bear Formation, Roysalt Formation, and Beta Island Member are proposed.

The Eocene palaeodrainage succession is placed in the Eundynie Group, and the post-Eocene succession in the Redmine Group. The Eundynie Group in the Lefroy Palaeodrainage consists of the non-marine to marginal marine Hampton Sandstone and Pidinga Formation, and Princess Royal Spongolite. In the Cowan Palaeodrainage, the Eundynie Group consists of the Werillup Formation, Norseman Limestone, and Princess Royal Spongolite. The Redmine Group consists principally of the clastic Revenge Formation. Carbonate units within the Redmine Group comprise the Cowan Dolomite in Lake Cowan (formerly placed in the Eundynie Group) and the Gamma Island Formation in Lake Lefroy. These formations are of probable Miocene age. Pliocene and younger evaporites are named the Roysalt and Polar Bear Formations in Lakes Lefroy and Cowan respectively. Gypsum dunes on Lake Lefroy comprise the Beta Island Member of the Roysalt Formation.

Introduction

Chains of linear playa lakes are a prominent physiographic feature of the Kambalda and Norseman area (Fig 1). The subject of investigation since Woodward (1897), these lake chains are interpreted as the remnants of palaeodrainage systems as first proposed by Gibson (1909). Little published data exists on the sediments in the palaeodrainages.

Recent drilling by Western Mining Corporation (WMC) during exploration for Archaean gold and nickel deposits has provided data on the stratigraphy of the Lefroy and Cowan palaeodrainages. These data allow the resolution of the relationship between the marginal stratigraphy of the Eucla and Bremer Basins.

The aim of this paper is to describe the stratigraphy of Lakes Lefroy, Cowan, and Dundas and their adjacent areas; revise the definition of the Eundynie Group (Cockbain 1968a); introduce the new terms Redmine Group, Revenge, Gamma Island, Polar Bear and Roysalt Formations, and Beta Island Member; and clarify stratigraphic relationships along the boundary of the Eucla and Bremer Basins. The sedimentary facies and evolution of the palaeodrainage fill are the subject of a separate paper (Clarke in press).

The paper is based of geomorphological mapping the Lake Lefroy area, logging of percussion diamond and air-core drill holes, and petrography. Palynological analysis of organic rich samples provided biostratigraphic control.

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Regional Setting

Lakes Lefroy, Cowan, and Dundas occur in the southeastern part of the Archaean Yilgarn Craton, and are within the palaeodrainage network defined by Bunting *et al.* (1974) and Van de Graaff *et al.* (1977). Lake Lefroy occurs within the Lefroy palaeodrainage, and Lakes Cowan and Dundas occur in the Cowan palaeodrainage. The bedrock surface beneath the lake surface defines a V-shaped palaeovalley (Figure 2).

Stratigraphy

Eundynie Group

The presence of Tertiary marine sediments in the Norseman and Lake Dundas region has been recognised since early this century (Campbell 1906). They have not previously been reported from beneath Lake Lefroy, although they are known from further east (Griffin 1989). The only outcrops of marine sediments in Lake Lefroy occur near Loves Find (Locality 7, Figure 1).

Eocene carbonates and spongolites in Lake Cowan were termed the Eundynie Group (Figure 3) by Cockbain (1968a). The usage is here expanded to include all Eocene sediments in palaeodrainages marginal to the Eucla and Bremer Basins. The Eundynie Group is thus laterally equivalent to the Eucla Group (redefined by Benbow *et al.*, in press) of the Eucla Basin, and the Plantagenet Group (Cockbain 1968b) of the Bremer Basin. Some of the formations extend laterally from one group to another. Thus, the Princess Royal Spongolite, Pidinga Formation and Hampton Sandstone occur in the Eucla and Eundynie Groups, and the Werillup Formation occurs in both the Plantagenet and Eundynie Groups.

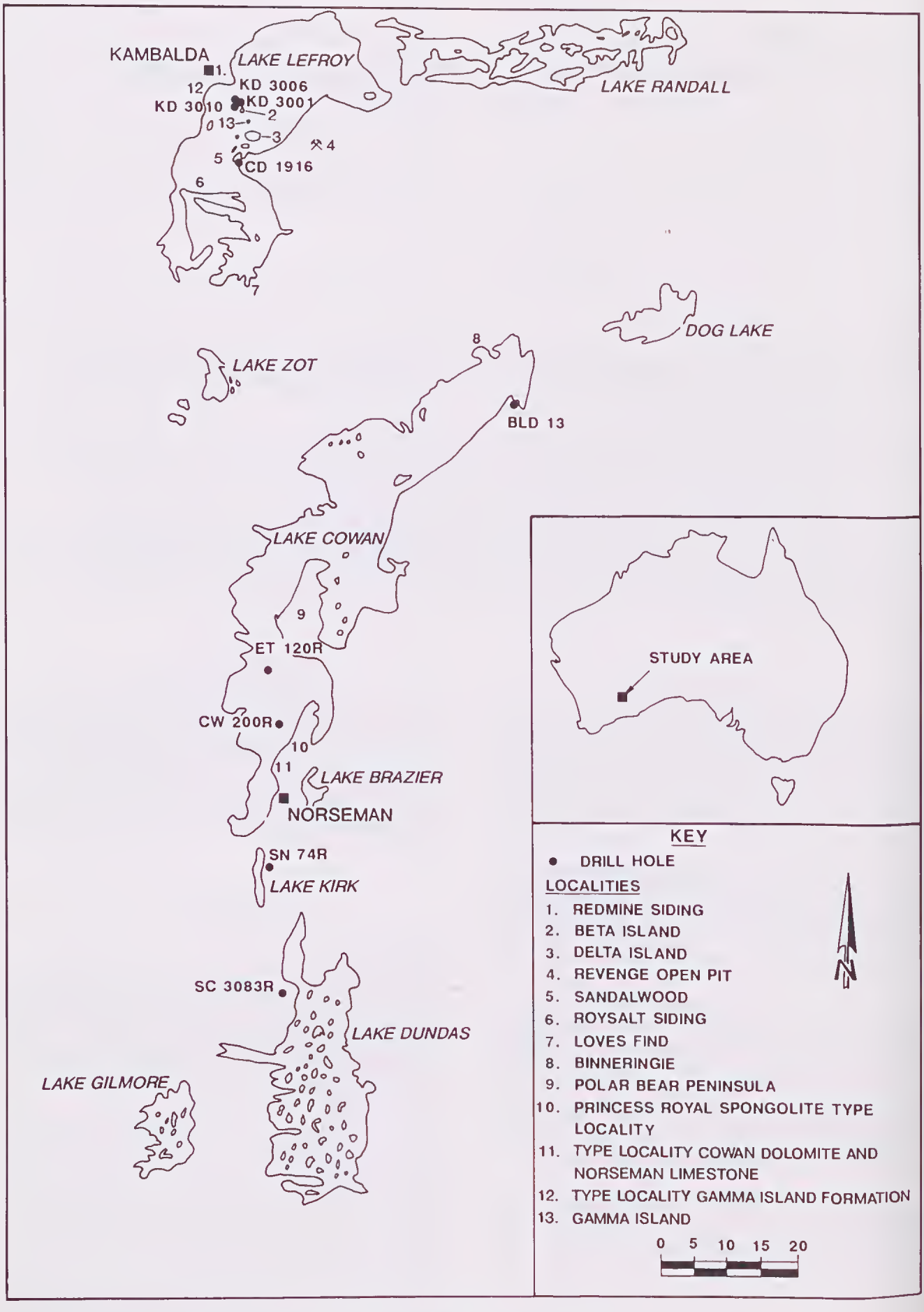

Figure 1. Locality map, showing Lakes Lefroy, Cowan and Dundas.

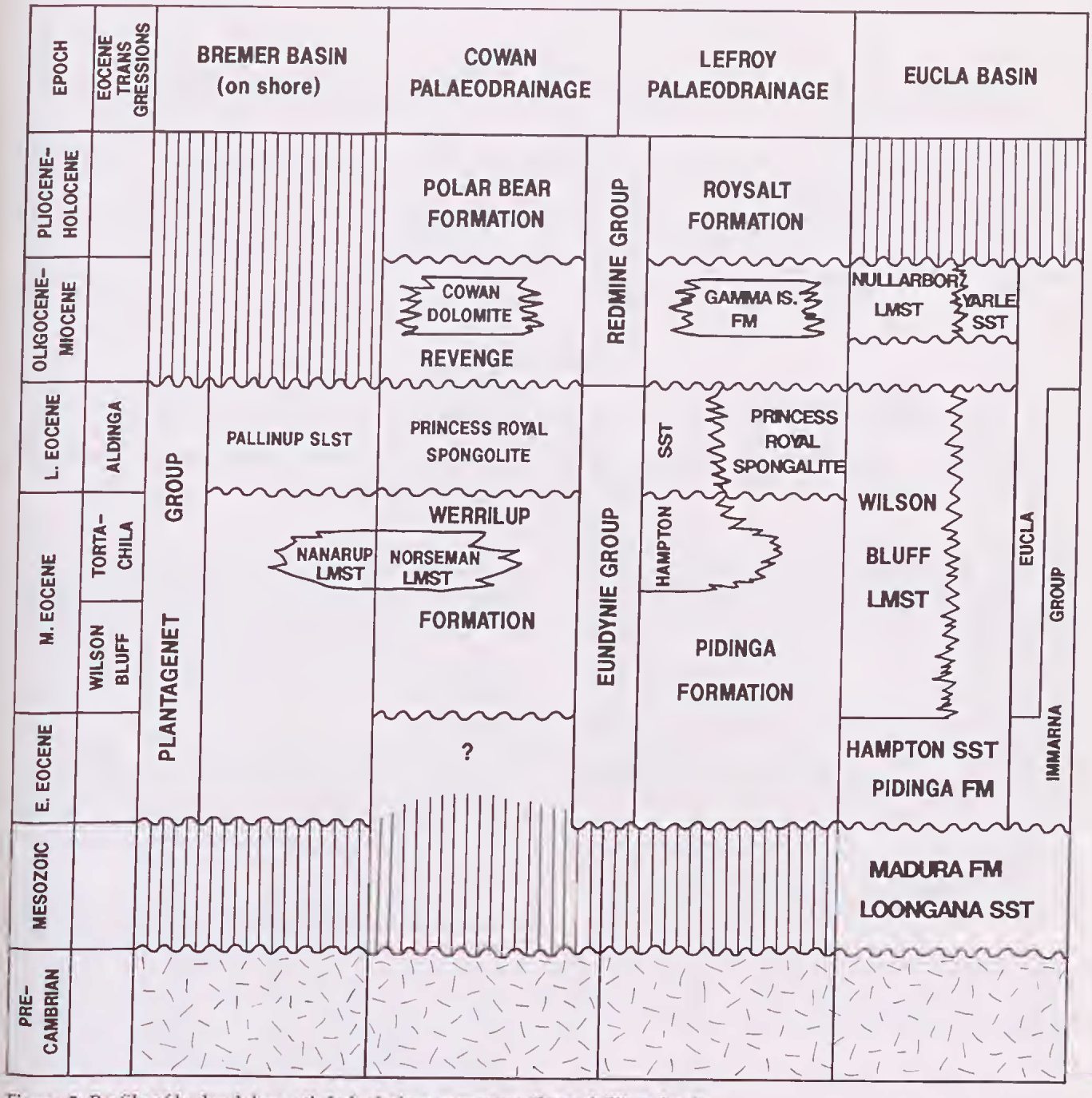

Figure 2. Profile of bedrock beneath Lake Lefroy causeway (from drilling data).

The Eundynie Group has maximum thicknesses of about 100 metres in both the Cowan and Lefroy palaeodrainages, and rests unconformably on Archaean and Proterozoic basement.

The Cowan Dolomite (Fairbridge 1953) was placed in the Eundynie Group by Cockbain (1968a). Drilling by WMC however indicates that the unit occurs within the later Tertiary lacustrine sequence, and is thus part of the overlying Redmine Group.

Pidinga Formation

Numerous names have been proposed for the Eocene sediments in the palaeodrainages of the Yilgarn Craton. Non marine sediments of Eocene age were named the Rollos Bore Beds by Balme and Churchill (1959), after the type locality near Coolgardie. Hocking and Cockbain (1990) extended the Rollos Bore Formation to include all similar lithologies in palaeodrainages on the Yilgarn Craton. Kern and Commander (in press) reviewed problems with the Rollos Bore locality as a type section, and proposed that the name Wollubar Sandstone, based on work in the Roe and Yindarlgooda palaeodrainages, be used in its place. Similar lithologies are present in the Rebecca and Raeside palaeodrainages to the northeast (Smyth and Button 1989).

The multiplicity of stratigraphic terms for Eocene palaeodrainage sediments along the margins of the western part of the Eucla Basin contrasts with that of the eastern part. In the eastern palaeodrainages, the lignitic marginal marine to non-marine sediments are all placed into the Pidinga Formation, and the non-lignitic, predominantly coarse-grained marginal marine to non-marine sediments Hampton Sandstone (Benbow *et al.* in press). This is practice is continued in this paper.

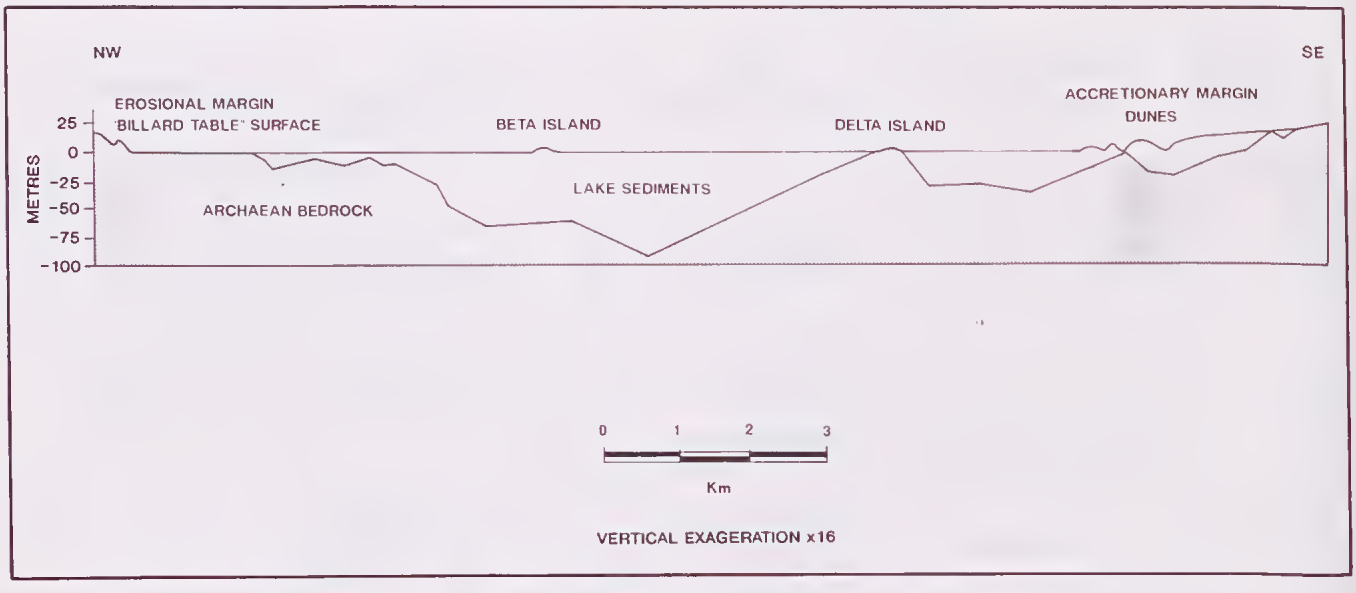

Figure 3. Stratigraphic correlations for the Eucla Platform, palaeodrainage, and Bremer Basin.

In the Lefroy palaeodrainage, the Pidinga Formation consists of laminated red-brown to green silts, white, grey or black clays and silts, and lignite. Gravelly, lignitic sand bodies are locally common. Authigenic pyrite is common throughout the sequence. Organic content varies from very high in lignites to low in white clays. The organic matter occurs as dispersed and comminuted fragments, woody material (most commonly roots, but also stems, seeds, and leaves), and lignite. Rare siliceous spicules are sometimes present. Marine fossils are absent from marginal tributaries such as the Mt Morgan palaeodrainage. Proportions of different lithologies are highly variable. Sedimentary structures, apart from faint laminations, are rare. Thin interbedded gravels are locally present. Scattered quartz granules occur throughout the sequence. A palynomorph assemblage containing 26 species belonging to 12 genera has been recovered from the Pidinga Formation in Lake Lefroy has been described by Parker (1988a, b) and Harris (1989).

The Pidinga Formation rests unconformably on Archaean basement, and interfingers with the Hampton Sandstone. In Lake Lefroy the formation reaches a maximum known thickness of 60 metres in CD 1916.

Palynomorphs described by Parker (1988b) from the Pidinga Formation in Lake Lefroy range in age from Early to Late Eocene. Similar ages were recorded by Balme and Churchill (1959) at Rollos Bore, and by Smyth and Button (1989) from the Rebecca and Raeside palaeorivers.

The Hampton Sandstone interfingers with the Pidinga Formation. The equivalent formation in the Bremer Basin and Cowan Palaeodrainage is the Werillup Formation.

Hampton Sandstone

The Hampton Sandstone is a widespread unit at the base of the Tertiary succession of the Eucla Basin (Lowry 1970). Benbow (1990a) described Hampton Sandstone interfingering with and overlying Wilson Bluff Limestone and spongolites (equivalent to the Princes Royal Spongolite below). Its presence in the Lefroy Palaeoriver to the west of Kambalda was recognised by Jones (1990). The formation is absent from the Cowan palaeoriver.

The Hampton Sandstone consists of fine to gravelly quartz sand. The unit is sparsely to moderately fossiliferous; the most common fossils are siliceous sponge spicules. Opalised gastropods, foraminifera, calcareous sponge spicules, together with brachiopod and echinoderm fragments, are also present. The greatest thickness of Hampton Sandstone yet encountered in Lake Lefroy is 24 metres in KD 3001 (Figure 4).

The Hampton Sandstone overlies and interfingers with the Pidinga Formation and Princess Royal Spongolite. It is most readily differentiated from sands in the Pidinga Formation by the abundance of carbonaceous matter in the latter. Differentiation from the Princess Royal Spongolite is based on the higher sand and lower spicule content of the Hampton Sandstone.

Jones (1990) cited palynological and micropalaeontological data which indicate a Middle to Late Eocene age for the Hampton Sandstone. This age indicates that the formation is pene-contemporaneous with the Pidinga Formation. The lower part of the Hampton Sandstone is correlated with the Tortachila transgression and the upper part with the Aldinga transgression of McGowran (1989). The Pidinga Formation interfingers with the Hampton Sandstone in the eastern and central parts of the Eucla Basin (Benbow *et al.* in press). Sand and sandstones in the Werillup Formation are equivalent to the Hampton Sandstone in the Bremer Basin and Cowan Palaeodrainage.

Werillup Formation

The Werillup Formation (Cockbain 1968b) comprises the basal part of the Plantagenet Group in the Bremer Basin. The formation is widespread along the south coast of Western Australia. The lignitic and carbonaceous sediments of Lake Cowan are correlated with the Werillup Formation because of their similar stratigraphic position, lithology, and depositional environment.

The Werillup Formation consists of carbonaceous clays, silts and sands, together with lignite lenses. A palynological assemblage of 84 species from 57 genera has been recovered from the Werillup Formation at Norseman (Parker 1988b, Harris 1989). The presence of 12 dinoflagellates species belonging to 11 genera was reported by Harris (1989). Siliceous sponge spicules and insect remains are also locally present.

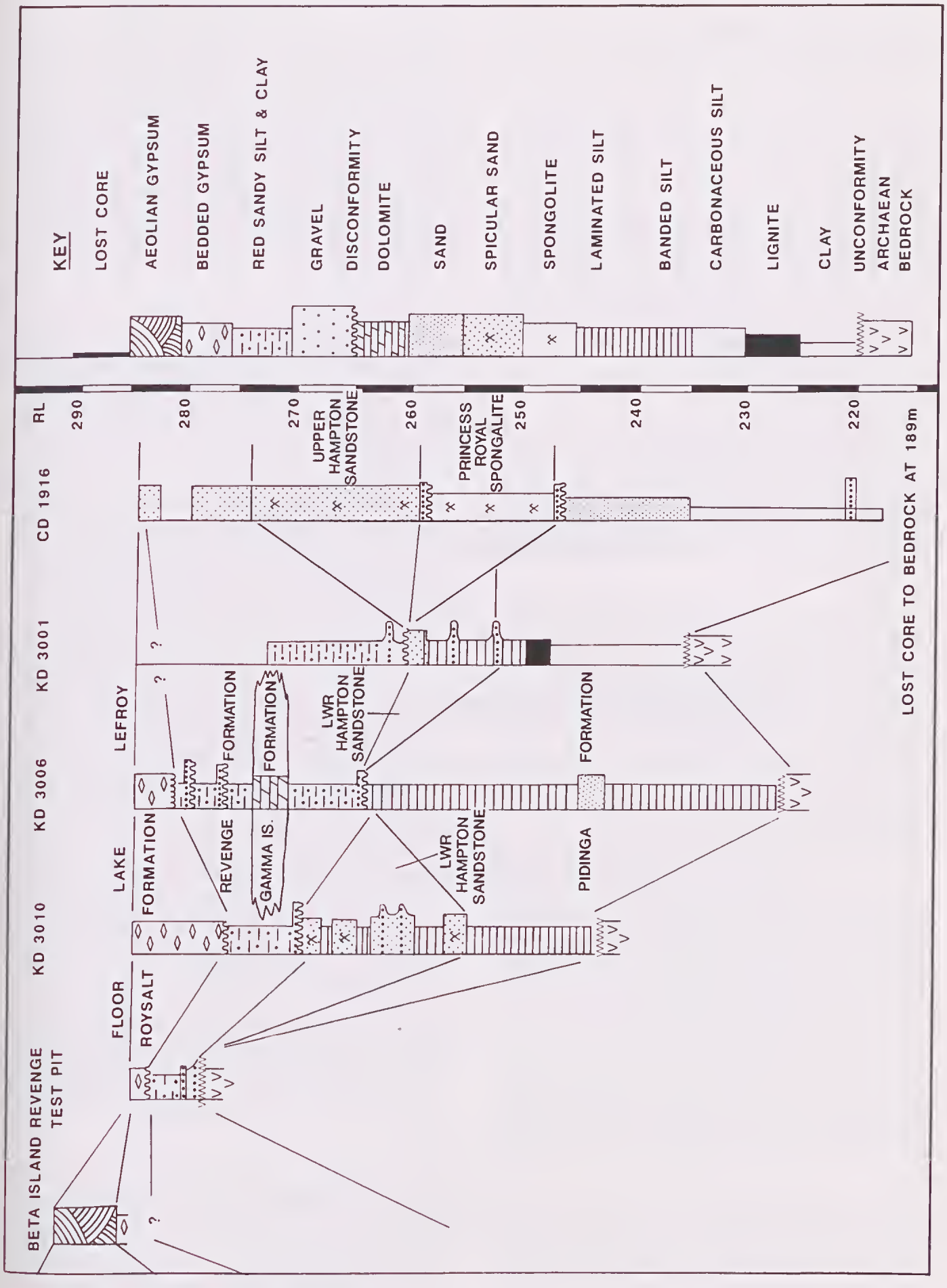

Figure 4. Sub-surface sequence for Lake Lefroy.

Limestones interfingering with the lower part of the Werillup Formation are termed the Nanarup Limestone Member along the south coast and Norseman Limestone in and around Lake Cowan.

The Werillup Formation rests unconformably on Archaean and Proterozoic basement. The formation is disconformably overlain in the palaeodrainages by the Princess Royal Spongolite. Along the south coast it is overlain by the Pallinup Siltstone.

McGowran (1989) demonstrated that the Nanarup Limestone was Middle Eocene. This suggests that clastics underlying the Nanarup Limestone may be Early Eocene, and those overlying late Eocene. Middle Eocene to Late Eocene palynomorphs were described by Parker (1988b) and Harris (1989) from the Werillup Formation from Lakes Cowan and Dundas. The Werillup Formation is equivalent to the Pidinga Formation and Hampton Sandstone of the Lefroy Palaeodrainage and Eucla Basin.

Norseman Limestone

The Norseman Limestone (Gregory 1916) is a fossiliferous marine carbonate that crops out along the south eastern margins of Lake Cowan, and also occurs to the east in Dog Lake (Hooper 1959). Stratigraphic relationships are not evident at the type locality (Clarke *et al.* 1948), but drilling by WMC has revealed that the formation is widespread beneath Lake Cowan (see two drill holes ET120R, CW200R and SN74R in Figure 5).

The Norseman Limestone varies from skeletal wackestone and grainstone to calcareous sandstone. Fossils include bryozoans, gastropods, bivalves, brachiopods, and foraminifera. Cementation varies from complete to nonexistent. Rocks at the type locality are silicified, and patchy dolomitisation has occurred in drill hole BLD 13. The formation beneath Lake Cowan, even though largely uncemented, is extensively dolomitised. Trough cross bedding is well developed in outcropping calcarenites near the site of BLD 13 (Figure 6a). Glauconitic material is present in minor amounts, most commonly near the base and top of the formation. The Norseman Limestone reaches a maximum known thickness of 37 metres beneath Lake Cowan in drill hole ET 120R.

Previously unclear stratigraphic relationships have been resolved by drilling in and around Lake Cowan. In BLD 13, the Norseman Limestone gradationally overlies lignitic siltstone of the Werillup Formation and is separated from silicified Princess Royal Spongolite by a thin bed of sandy Werillup Formation. The Werillup Formation overlying the Norseman Limestone towards the middle of Lake Cowan (Figure 5) is, however, up to 30 metres thick.

Foraminiferal data reported by Cockbain (1968a) indicated a Late Eocene age. Palynological studies by Parker (1988b) indicated that the Werillup Formation immediately underlying the Norseman Limestone in BLD 13 is of Early to Middle Eocene age. This indicates that the formation is Middle Eocene or younger. Late Eocene lignitic sediments (Harris 1989) are found overlying the Norseman Limestone.

Cockbain (1968a) correlated the Norseman Limestone with the lithologically similar Toolina Limestone in the Eucla Basin. The Norseman Limestone is however more likely a correlative of the Nanarup Limestone Member of the Werillup Formation in the Bremer Basin. A Middle Eocene age (Tortachila transgression) has been determined for the Nanarup Limestone Member (McGowran 1989). The southern extension of the Cowan Palaeodrainage into the Bremer Basin at Esperance contains calcareous marine sandstones in the lower Werillup Formation (Cockbain 1967; Morgan & Peers 1973). These are almost certainly equivalent to the Nanarup and Norseman Limestones. This stratigraphic position is contrary to Hocking (1990a), who placed the Nanarup Limestone at the top of the Werillup Formation. The two limestones are thus likely to be the same unit, although more extensive drilling is necessary to confirm this correlation. It is recommended that Nanarup Limestone Member be abandoned as a stratigraphic term, and the earlier name Norseman Limestone Formation be used for all marine carbonates that interfinger with the Werillup Formation.

Princess Royal Spongolite

The Princess Royal Spongolite (Glauert 1926) occurs extensively in palaeodrainages along the eastern margin of the Eucla Basin (Jones 1990). The Formation is common only along the margins of Lefroy and Cowan palaoedrainages, having been removed by erosion from much of the central portions, but is more continuous further east. The Princess Royal Spongolite is absent from tributaries such as the Mt Morgan Palaeodrainage.

Lithologies consisting of greater than 50% siliceous sponge spicules with lesser amounts of silt and clay overlying or interfingering the Pidinga and Werillup Formations are recognised as Princess Royal Spongolite. Minor quartz sand and glauconitic peloids are also present. Other fossils, apart from centric diatoms, are absent. The only description of the spicule assemblage is that of Hinde (1910), who recognised 15 genera at the type locality.

The Princess Royal Spongolite reaches a thickness of 12 metres beneath Lake Lefroy in drill hole CD 1916 (Figure 4). A thickness of 21 metres on the northern shores of Lake Cowan near Bingeringie was reported by Hooper (1959).

A disconformable contact marked by a gravel bed separates the Princess Royal Spongolite from the Pidinga Formation in drill hole CD 1916. The Hampton Sandstone interfingers with the Formation at Loves Find, and overlies it in CD 1916. The Princess Royal Spongolite onlaps directly onto Archaean basement along the shores of Lake Lefroy near Loves Find (Figure 6b).

Palynomorphs described by Hos (1977) from Harris Lake on the margins of the Eucla Basin gave a Late Eocene age for the Princess Royal Spongolite. The laterally equivalent Pallinup Siltstone in the Bremer Basin contains a Late Eocene marine fauna (Cockbain 1968b). The Princess Royal Spongolite was probably deposited during the Aldinga Transgression of McGowran (1989).

The formation passes laterally into the Wilson Bluff Limestone to the east (Jones 1990), while the Pallinup Siltstone of the Bremer Basin passes into the Toolina Limestone of the Eucla Basin, east of Israelite Bay (Lowry 1970). The Bring Member of the Pidinga Formation (Benbow 1986) is the time-equivalent lithology in the Tallaringa Palaeodrainage of the eastern Eucla Basin.

Redmine Group

Successions of non-fossiliferous, yellow, brown, and red alluvial and lacustrine sediments were mentioned by Smyth and Button (1989) and Jones (1990). This paper formalises the stratigraphy of the post Eocene succession in Lakes Lefroy and Cowan. The names and their coordinates are taken from localities on the Lefroy 1: 100 000 geological map (sheet 3235), and are shown in Figure 1.

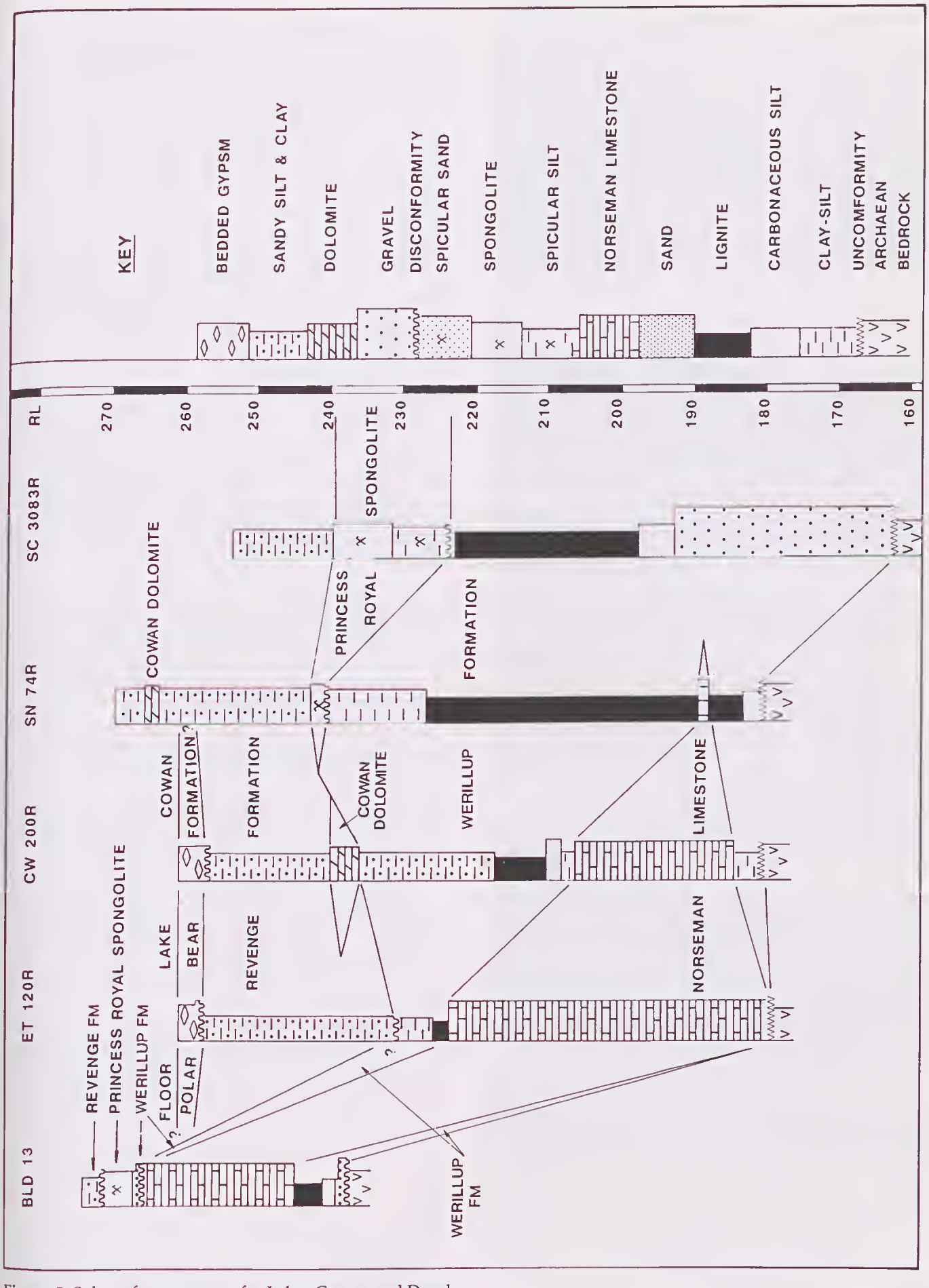

Figure 5. Sub-surface sequence for Lakes Cowan and Dundas.

Figure 6. (A) Outcropping Norseman Limestone on shore of Lake Cowan, near drill hole BLD 13. (B) Outcropping Princess Royal Spongolite and upper Hampton Sandstone on shore of Lake Lefroy, near Loves Find. (C) Outcropping fenestral dolomite of Gamma Island Formation at type locality on Lake Lefroy. (D) Cross-bedded gypsarenite of Beta Island Member, Beta Island.

The Eocene sediments in the Lefroy and Cowan palaeodrainages lack iron oxide bearing sediments; iron oxides and hydroxides are common in the post-Eocene sediments succession. Eocene sediments are fluvial to shallow marine in origin, contrasting with the predominantly lacustrine sediments of the post-Eocene succession. The Eocene palaeodrainage succession can also be correlated with equivalent units on the Eucla Basin, but this cannot be done with the post-Eocene sediments. These differences are sufficient to justify placing the post-Eocene succession into a separate lithostratigraphic unit, the Redmine Group.

The name Redmine Group is taken from Redmine Siding, the railway siding at the Kambalda Nickel Operations concentrator mill (GR 740488). The Redmine Group rests disconformably on the Eocene sediments of Lake Lefroy, up to 20 metres of relief has been incised into the top of the Eundynie Group (Figure 4).

The Redmine Group comprises the post-Eocene portion of palaeodrainage sediments. Red clastic facies occur in Lake Lefroy, further east in the Lefroy Palaeoriver (Jones 1990), and in Lake Cowan. Dark green-grey sediments of presumed post-Eocene age are also present in Lake Cowan. Red-brown sediments in the Raeside and Rebecca palaeodrainages (Smyth & Button 1989) may be equivalent to the Redmine Group. Similar post-Eocene sediments, apart from possible Cowan Dolomite (see below), have not been demonstrated in the Lake Dundas area, but it is highly likely that they are present.

The Redmine Group in the sub-surface consists of predominantly red-brown silts, clays, sand, and gravel. Some sands and gravels are cemented by iron oxides. Dark green clastics are locally present within the group in Lake Cowan. Outcrops are similar, but cemented by iron oxides. Interbedded lenses of oolitic to fenestral dolomite are present. Outcrops of dolomites and iron cemented clastics common along the northern and western margins of Lake Lefroy are also included in the Redmine Group. The upper part of the group contains bedded gypsum deposits and gypsum aeolianites.

Up to 26 metres of predominantly red-brown sediments overlying the Eocene succession are present beneath Lake Lefroy. Similar thicknesses occur beneath Lake Cowan.

The base of the Redmine Group rests disconformably on palaeotopography eroded into Eocene sediments or unconformably on Archaean basement. The variable thickness of the Group is interpreted to be the result of infill of a variably eroded surface. The upper limit of the Redmine Group is the present depositional surface.

The Redmine Group post-dates the late-Late Eocene marine sediments on which it rests, with deposition continuing through to the present. Earliest Pliocene palynomorphs are present in the upper part of the group in Lake Lefroy (Parker 1988a).

The Redmine Group comprises, the Cowan Dolomite together with Revenge, Gamma Island, and Roysalt Formations.

Revenge Formation

The formation is named after Revenge open pit, shown on the Lefroy map sheet at GR 765412, but in reality occurring 500 metres further east at GR 770412.

The Revenge Formation occurs widely beneath Lakes Lefroy and Cowan, and also beneath some of the smaller lakes marginal to them. Similar lithologies occur along the length of the Lefroy palaeodrainage. Lateral continuity between the Lefroy and Cowan palaeodrainages is probable, hence the use of the same stratigraphic name for these lithologies in the two palaeodrainages. The type locality is exposed in the walls of the Revenge open pit, where a thickness of 5 metres is attained.

The Revenge Formation beneath Lakes Cowan and Lefroy consists largely of massive to faintly laminated red-brown silts. Small lenses of fine sand and ferruginous sandstone occur within the formation beneath Lake Lefroy. Red sands and ferruginous sandstones predominate along the margins of the lake. Pebble beds are present at the base of the sequence, and also at intervals higher in the section; these represent internal disconformities. Dark grey-green coloured sediments are locally present. Outcrops of iron oxide cemented conglomerate and sandstone. These well-indurated sediments are marginal facies of the Revenge Formation. The Revenge Formation in Lake Cowan is composed of similar lithologies to those found in Lake Lefroy (Figure 5).

The formation reaches a known thickness of 17 metres in Lake Lefroy. Marginal facies of the Revenge Formation exposed on the shores of Lake Lefroy occur at elevations 8 metres above the present lake surface, indicating original thicknesses at least 8 metres greater than that presently preserved. The formation may reach thicknesses of 25 metres in Lake Cowan (Figure 5).

The base of the formation rests unconformably on Archaean bedrock, as displayed in the Revenge open pit, or disconformably on Eocene sediments. The upper limit of the unit is the disconformable base of the overlying Roysalt Formation in Lake Lefroy and the Polar Bear Formation in Lake Cowan.

The oxidised nature of the Revenge Formation is not favourable for the preservation of palynomorphs, and none have been recovered. A lower limit for the formation is set by the underlying Late Eocene sediments, and the overlying Pliocene pollen assemblage in the Roysalt Formation (Parker 1988a). A Miocene age is favoured, given the widespread preservation of lacustrine sediments from this time elsewhere in Australia (De Deckker 1988). This also coincides with the last major transgression on the Eucla Basin that deposited the Nullarbor Limestone (Lowry 1970), the elevated base level resulting in lacustrine deposition within marginal palaeodrainages.

The Perkolilli Shale (Kern & Commander, in press) in the Roe Palaeodrainage is lithologically very similar, and is probably correlative with the Revenge Formation. The Miocene fluvial to marginal marine Plumbridge Formation (Hocking 1990b) and the marine Yarle Sandstone (Benbow 1990b) along the margins of the Eucla Basin are likely to be distal equivalents. Some of the numerous Cainozoic formations defined by Glassford (1987) from Yeelirie may be partly equivalent to the Revenge Formation.

Gamma Island Formation

The Gamma Island formation is named after Gamma Island, the local name for the Lake Lefroy island shown at GR 775539 on the Lefroy map sheet. The formation occurs patchily beneath Lake Lefroy, and along its northern and western margins. The shore of Lake Lefroy at the Newtown Creek estuary (Figure 1, 6c).

Lenses of oolitic (L. Killigrew, quoted by Loftus-Hills 1981) and fenestral dolomite are present in drill hole KD 3006 (Figure 4). White oncolitic, fenestral, peloidal, and massive dolomites to dolomitic carbonate mudstones are present on the margins and estuaries of Newtown, Merougil and Muldolia Creeks (Figure 1).

The thickness varies from at least 2 metres in the type locality, to 2.5 metres in KD 3006.

Boundary relationships are not exposed at the type locality. The Gamma Island Formation occurs within the Revenge Formation in KD 3006, and overlies it along the western shores of Lake Lefroy.

A Miocene age is favoured, given the widespread preservation of lacustrine sediments, especially carbonates, from this time elsewhere in Australia (De Deckker 1988).

The Gamma Island Formation is placed in a separate formation from other units in the Redmine Group because its marked lithological contrast to them, and for consistency of usage with equivalent units, the Cowan Dolomite in Lake Cowan, and the Garford Formation is the palaeodrainages of the eastern Eucla Basin (Benbow *et al.* in press). The lack of continuity between the otherwise similar lacustrine carbonates of Lakes Lefroy and Cowan justifies the use of different formation names.

Cowan Dolomite Formation

The relationship of the Cowan Dolomite (Fairbridge 1953) to the Norseman Limestone and Princess Royal Spongolite is not evident at the type locality, although the three units are spatially closely associated. Aircore drilling at Lake Kirk south of Norseman has revealed similar lithologies occurring at different levels with lacustrine sediments overlying the Princess Royal Spongolite. The formation is thus placed within the Redmine Group.

The Cowan Dolomite crops out along the shores of Lakes Cowan and Brazier. The formation consists of white to buff-coloured dolomite to dolomitic carbonate mudstone. The maximum thickness of the Cowan Dolomite is unknown, in SN 78R it is 2 metres thick. The Cowan Dolomite is equivalent to the Gamma Island Formation in Lake Lefroy. Small outcrops of dolomite in the Cowan palaeodrainage east of Salmon Gums (to the south of Lake Dundas) were correlated with the Cowan Dolomite by Doepel (1973).

The age of the formation is unknown, but is probably Miocene. Carbonate facies are common in Miocene lacustrine sediments elsewhere in Australia (De Deckker 1988), the Formation may be partly equivalent to the Miocene-Pliocene Garford Formation in palaeodrainages of the eastern Eucla Basin (Benbow *et al.* in press).

Roysalt Formation

The name Roysalt Formation is derived after Roysalt Siding, GR 688271, near the old Lake lefroy salt works. The unit occurs right across the floor of Lake Lefroy and on its margins. Type exposures of the formation occur in the walls of the Revenge open pit, where thicknesses of 1.5-2m are attained.

The Roysalt Formation consists of sandy silts and clays on the margins of Lake Lefroy, passing into bedded gypsum crystals in a silty, carbonaceous, and pyritic matrix towards the centre of the lake. Gypsum crystals in the lower part of the formation have grown together to form a boxwork structure. The sediments in the gypsum dunes have been separated into the Beta Island Member (see below).

The greatest known thickness is 9 metres (KD 3010, Figure 4). Horizontally bedded gypsum occurs up to 1 metres above the present lake floor in gypsum dune islands, where overlying gypsum aeolianite has protected the sediments from erosion.

The Roysalt Formation rests disconformably on the erosional top of the Revenge Formation. Preservation of similar sediments above the current lake floor in gypsum dune islands indicates a minimum thickness of 1 metres for eroded material, which demonstrates that the current lake floor is an erosional surface.

Palynomorphs from the base of the formation at Revenge give a Pliocene age (Parker 1988a). Deposition of the Roysalt Formation may have continued into the Holocene.

The Roysalt Formation is a time equivalent of Pliocene sediments at Lake Tay, west of Lake Dundas (Bint 1981), the Darlot Formation (in particular the Miranda Member) at Yeelirie (Glassford 1987), and of the Pliocene Narlaby Formations (Benbow *et al.* in press) in South Australia. The formation passes laterally into, and interfingers with fluvial and aeolian clastic sediments along the margins of Lake Lefroy. The Polar Bear Formation is the equivalent unit in Lake Cowan (see below). Different formation names are used owing to the lack of continuity between the different evaporitic lithologies of Lakes Cowan and Lefroy.

Beta Island Member

The name Beta Island Member is taken from Beta Island, the local name for the gypsum dune island at GR 765412, site of the Lake Lefroy land sailing club.

The Beta Island Member comprises the gypsum dunes that occur across the lake floor and on its western margins. Most islands on Lake Lefroy are at least in part gypsum dunes. Some, such as Delta Island, are composite, with a bedrock core and accreted gypsum and silica dunes. The member also occurs along the lake shore, particularly at Sandalwood. The 8 metres high cliffs that surround most of the margin of Beta Island (Figure 6d) comprise the type locality for the Member.

The Beta Island Member is composed of gypsum cemented, steeply cross-bedded, gypsum sand. Quartz sand, silt and clay are minor components. Individual cross bed sets range in thickness from 4-8 metres. Two gypcrete horizons are present within the member on Beta Island. The uppermost horizon corresponds with the present surface in each case.

The member reaches a maximum thickness of 11 metres on Oyster Island.

The Beta Island Member overlies the Roysalt Formation. The contact is exposed approximately 1 metre above the lake floor on Beta Island where cross bed toes transgress across flat bedded gypsum. The present land surface corresponds with the top of the member.

The age of the Beta Island Member is unknown. The gypsum dunes must post date the Pliocene and younger Roysalt Formation from which it is derived. The member is currently being eroded, with cliff faces developed on nearly all exposures. Mixed quartz-clay dunes have also partly buried gypsum dunes on Delta Island and at Sandalwood; the member is thus unlikely to be Holocene in age. Bowler (1976) dated many gypsum dunes in arid Australia at 13-18 000 years BP, a possible age for the Beta Island Member.

The Beta Island Member is closely associated with siliciclastic dune sediments, both on the lake islands and shores. The gypsum dunes underlie siliciclastic dunes in many localities, the stratigraphic relationship between the Beta Island Member and older, degraded dune systems is unclear. The member is equivalent to part of the Miranda Member of the Darlot Formation at Yeelirie (Glassford 1987).

Polar Bear Formation

The Polar Bear Formation is named after Polar Bear Peninsula, the large peninsula extending out into Lake Cowan north of Norseman. The Polar Bear Peninsula occurs on the Cowan topographic sheet at GR 870680. The Polar Bear Formation occurs across the floor of Lake Cowan and on its margins. The type section is in CNG air core hole ET 120R, where the formation is 3 metres thick.

The Polar Bear Formation consists of sandy silts and clays along the edges of Lake Cowan, and bedded gypsum crystals in a silty matrix towards the centre of the lake. Low relief gypsum dunes occur in some localities along the floor of Lake Cowan and its margins. These dunes are generally less than 2 metres high.

The Formation is 3 metres thick in ET 120R and CW 200R (Figure 5). Scattered low relief gypsum dunes along the margins of the lake and across its floor add another 2 m.

The Polar Bear Formation rests disconformably on the erosional top of the Revenge Formation. The top of the formation is defined by the present land surface.

The Formation is earliest Pliocene to Holocene in age, by analogy with the lithologically and stratigraphically equivalent Roysalt Formation in Lake Lefroy. Early Pliocene pollen in sediments in Lake Tay 125 kilometres to the south-west (Bint 1981) indicate the presence of non-arid lake shore vegetation. This indicates that gypsum precipitation in Lake Tay began after the Early Pliocene. Thus the base of the Polar Bear Formation in Lake Cowan (about half way between Lakes Lefroy and Tay), may be slightly younger than earliest Pliocene.

Conclusions

This proposed stratigraphic framework is intended to simplify and clarify the stratigraphy of the Cowan and Lefroy palaeodrainages, and relate them to the stratigraphy of the Bremer and Eucla Basins. It is hoped that the same stratigraphic nomenclature, with appropriate modifications for local units (particularly in the Redmine Group) can be extended to other palaeodrainages along the margins of the Bremer and Eucla Basins.

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References

Balme B E & Churchill D M 1959 Tertiary sediments at Coolgardie, Western Australia. Journal of the Royal Society of Western Australia 42: 37-43.

Benbow M C 1986 Tallaringa map sheet. Geological Atlas of South Australia, 1: 250 000 series. South Australian Department of Mines and Energy, Adelaide.

Benbow M C 1990a Tertiary Coastal Dunes of the Eucla Platform,Australia. Geomorphology 3: 9-29.

Benbow 1990b The Yarle Sandstone: a Miocene coastal terrigenous sequence of the Eucla Platform. Quarterley Geological Notes of the Geological Survey of South Australia 113: 2-6.

Benbow M C, Lindsay J M & Alley N F in press Bight and Duntroon basins, Eucla Basin and palaeodrainage. In: The Geology of South Australia (ed Johns R K) Geological Survey of South Australia Bulletin, South Australian Department of Mines and Energy, Adelaide.

Bint A N 1981 An Early Pliocene pollen assemblage from Lake Tay, South-western Australia, and its phytogeographic implications. Australian Journal of Botany 29: 277-91.

Bowler J M 1976 Aridity in Australia: Age, Origins and Expression in Aeolian Landforms and Sediments. Earth Science Reviews 12: 279-310.

Bunting J A, Van de Graaff W J E, & Jackson M J 1974 Palaeogeography of the Eastern Goldfields, Gibson Desert and Great Victoria Desert. Geological Survey of Western Australia Annual Report 1973: 45-50.

Campbell W D 1906 The geology and mineral resources of the Norseman district, Dundas Goldfield. Western Australian Geological Survey Bulletin 21. Geological Survey of Western Australia, Perth.

Clarke E De C, Teichert C & McWhae J R H 1948 Tertiary deposits near Norseman, Western Australia. Journal of the Royal Society of Western Australia 32: 85-103.

Clarke J D A In press Evolution of the Lefroy and Cowan palaeodrainages, Western Australia. Australian Journal of Earth Sciences.

Cockbain A E 1967 *Asterocyclina* from the Plantagenet Beds near Esperance, WA. Australian Journal of Science 30: 68-69.

Cockbain A E 1968a Eocene foraminifera from the Norseman Limestone of Lake Cowan, Western Australia. Geological Survey of Western Australia Annual Report 1967, 59-60.

Cockbain A E 1968b The stratigraphy of the Plantagenet Group, Western Australia. Geological Survey of Western Australia Annual Report 1967, 99-101.

De Deckker P 1988 Large Australian lakes during the last 20 million years: sites for petroleum source rock or metal ore deposition, or both? In: Lacustrine Petroleum Source Rocks (eds Fleet A J, Kelts K, & Talbot M R) Geological Society Special Publication, London 40: 45-58.

Doepel J J G 1973 Explanatory notes on the Norseman 1: 250 000 geological sheet, Western Australia. Geological Survey of Western Australia, Perth.

Fairbridge R W 1953 Australian Stratigraphy. University of Western Australia Text Books Board, Perth.

Gibson C G 1909 The geological features of the country lying along the route of the proposed transcontinental railway in Western Australia. Geological Survey of Western Australia Bulletin 37.

Glassford D K 1987 Cainozoic stratigraphy of the Yeelirie area, northeastern Yilgarn Block, Western Australia. Journal of the Royal Society of Western Australia 70: 1-24.

Glauert L 1926 A list of Western Australian fossils, supplement No. 1: Western Australian Geological Survey Bulletin 88: 36-71.

Gregory J W 1916 The age of the Norseman Limestone, Western Australia. Geological Magazine 3: 320-321.

Griffin T J 1989 Explanatory notes on the Widgiemooltha 1: 250 000 geological sheet, Western Australia. Geological Survey of Western Australia Record 1989/4.

Harris W K 1989 Palynology of seven samples from the Norseman area. Unpublished report, Kambalda Nickel Operations Geological Exploration File 9/G/6L.

Hinde G J 1910 On fossil sponge spicules in a rock from the Deep Lead (?) at Princess Royal Township, Norseman District, Western Australia. Geological Survey of Western Australia Bulletin 36: 7-24.

Hocking R M 1990a Bremer Basin. In: Geology and Mineral Resources of Western Australia: Geological Survey of Western Australia Memoir, Perth 3: 561-563.

Hocking R M 1990b Eucla Basin. In: Geology and Mineral Resources of Western Australia: Geological Survey of Western Australia Memoir, Perth 3: 548-561.

Hocking R M & Cockbain A E 1990 Regolith. In: Geology and Mineral Resources of Western Australia. Department of Mines Western Australia Memoir, Perth 3: 591-601.

Hooper K 1959 The marine Tertiary rocks of Bingeringi at the north end of Lake Cowan, Western Australia. Carlton University Department of Geology Paper, Ottowa 59-3.

Hos D P C 1977 Samples from Harris Lake, Western Australia. University of Western Australia Palynology Report 351.

Jones B G 1990 Cretaceous & Tertiary sedimentation on the western margin of the Eucla Basin. Australian Journal of Earth Sciences 37: 317-329.

Kern A M & Commander P 1993 Cainozoic stratigraphy in the Roe Palaeodrainage of the Kalgoorlie region, Western Australia. Geological Survey of Western Australia, Perth. Professional Paper 34.

Loftus-Hills G 1981 Contingency report on the palynological work on the Lake Lefroy area by Dirk Hos. Kambalda Nickel Operations Geology Department unpublished technical report 1304.

Lowry D C 1970 Geology of the Western Australian part of the Eucla Basin. Geological Survey of Western Australia Bulletin 122. Geological Survey of Western Australia, Perth.

McGowran B 1989 The later Eocene transgressions in southern Australia. Alcheringa 13: 45-68.

Morgan K H & Peers R 1973 Explanatory notes on the Esperance-Modrain Island 1: 2500 000 geological sheet, Western Australia. Geological Survey of Western Australia, Perth.

Parker F 1988a Palynology of Samples from Lake Lefroy. Kambalda Nickel Operations Geology Department unpublished technical report 2922.

Parker F 1988b Palynology of selected drill hole samples from the Lake Lefroy area. Kambalda Nickel Operations Geology Department unpublished technical report 3000.

Smyth P R & Button A 1989 Gold Exploration in the Tertiary Palaeodrainage Systems of Western Australia. In: World Gold '89 (eds Bhappu R B & Harton R J). Gold forum on technology and practices. Proceedings of the First Joint International Meeting between the Society of Mining Engineers and the Australasian Institute of Mining and Metallurgy, Reno Nevada, p262-269. Society of Mining, Metallurgy and Exploration, Littleton, Colorado.

Van de Graaff W J E, Crowe R J, Bunting J A & Jackson M J 1977 Relict Early Cainozoic Drainage in arid Western Australia. Zeitschrift fur Geomorphologie N.F. 21: 379-400.

Woodward N P 1897 The Dry Lakes of Western Australia. Geological Magazine 4: 363-366.